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Abstract

Mediterranean Sea fisheries supply significant local and international markets, based largely on small pelagic fish, artisanal fisheries and aquaculture of finfish (mainly seabass and seabream) and shellfish (mussels and oysters).Fisheries and aquaculturecontribute to the economy of countries bordering this sea and provide food and employment to coastal communitiesemploying *ca* 600,000 people.Increasing temperatures and heat wave frequency are causing stress and mortality in marine organismsand ocean acidification is expected to worsen these effects, especially for bivalves and coralligenous systems. Recruitment and seed production present possible bottlenecks for shellfish aquaculture in the future since early life stages are vulnerable to acidification and warming. Although adult finfish seem able to withstand the projected increases in seawater CO_2, degradation of seabed habitats and increases in harmful blooms of algae and jellyfish might adversely affect fish stocks.Ocean acidification should therefore be factored into fisheries and aquaculture management plans. Rising CO_2 levels are expected to reduce coastalbiodiversity,altering ecosystem functioning and possibly impactingtourism being theMediterranean the world’s most visited region.Werecommendthat ocean acidification is monitored in key areas of the Mediterranean Sea, with regular assessments of the likely socio-economic impacts to build adaptive strategies for the Mediterranean countries concerned.

Keyword: Mediterranean, climate change, warming, acidification, ecosystemservices, fisheries, habitat loss,ecosystemvulnerability.

1. Introduction

The Mediterranean Sea has a restricted exchange of seawater with the Atlantic Ocean via the Strait of Gibraltar in the West and the Black Sea in the East and to a lesser extent with the Red Sea via the Suez Canal (Fig. 1). The region supports cold, temperate and sub-tropical biota and is a so called‘biodiversity hotspot’ with 7% of the world's known species living in 0.82% of the ocean area[1]. This exceptional biodiversitybenefits economic sectorssuch as tourism andcultural heritage. In addition, aquaculture and fisheries contribute to local and national income going back to thousands of years. Human-induced CO_2emissionis a global phenomenawith different regional consequences. The Mediterranean Sea is affected in several ways through climate change and ocean acidification.Mediterraneanacidification is already detectable [2,3] and combined with the rapid warming, the increase frequency of extreme weather events and the rapid increase of human population around its coasts have serious consequences for the region.

2. Mediterranean fisheries and aquaculture

Fisheries and aquaculture in the Mediterranean Sea represent 1% of world landings, and 2% in terms of economic value. While fishcatches have remained quite stable since the 1990's, aquaculture hasquadrupled in production reaching 20% of production in 2011 (Fig. 2). While aquaculture production is mainly supported by northern European countries, the fishery sector mainly comprises artisanal activities (~80% of the flotilla; [4]), being more common in southern Mediterranean countries.

Capture fishery

Pelagic fish account for 53% of the total Mediterranean catch (Fig. 3; about 460,000 tonnesin 2011) with landings dominated by sardine *(Sardinapilchardus*) and anchovy

(*Engraulisencrasicolus*) (Fig. 4).

Demersal fish make up 30% of landings,crustaceans 7% and molluscs(including cephalopods) comprise 10% of Mediterranean landings. The striped venus clam,*Chameleagallina* (around 20,000 tonnes yr^{-1}) is mainly harvested in the Adriatic Sea and constitutes 70% of molluscs landings. Small-scale fisheries dominate (> 60%) the fishing sector in the Mediterranean Sea.Capture fisheries and aquaculture in the Mediterranean Sea provide a central source of food and employment: they directly employ 250,000 and 123,000 in fisheries and aquaculture, respectively and employ about 210,000 people for secondary sector [4]. In this context, it is of foremost importance to assess the impacts of ocean acidification on these two economic sectors.

Aquaculture

Fish and mollusc production dominates Mediterranean aquaculture although crustaceans are also farmed. The production of gilthead seabream (*Sparusaurata*) has risen rapidly from 3,833 tonnes in 1990 to 143,295 tonnes in 2010 (worth approximately US$ 785 million). European seabass (*Dicentrarchuslabrax*) production rose from 2,944 t in 1990 to 131,509 t in 2010 (valued at US$ 786 million). In 2010, the main producers of gilthead seabream were Greece (43%), Turkey (20%) and Spain (13%), whereas the top three producers of European seabasswere Turkey (40%), Greece (28%) and Egypt (12%). In 2010, 81% of the total Mediterraneanmeagre (*Argyrosomusregius*) production was in Egypt [5].

The oyster *Ostreaedulis*has been farmed in the Mediterranean since the 1st century BC. But in the 1970s these oysters suffered mass mortalities due to pathogenic protozoans and have been progressively replaced in aquaculture by the Pacific oyster (*Crassostrea gigas*), as it is more resistant. Mediterranean bivalve yields increased greatly between the 1950's and the 1990's and have now stabilizedat around 180,000 t y^{-1}(Fig. 5).Italy produces 67% of the Mediterranean bivalve production, followed by Greece and France (Fig. 5). This production is dominated by the Mediterranean mussel (*Mytilusgalloprovincialis*),which represents almost three quarters of the total Mediterranean shellfish production (120,000 t y^{-1}; Fig. 5 C). Japanese carpet shell (*Ruditapesphilippinarum*; about 35,673 tonnes yr^{-1} with around 98% in Italy) and the Pacific cupped oyster are the other important cultivated species (8,000 t y^{-1} and 300 t yr^{-1} by Spain and France).

3. Human impacts

Multiple global, regional and local driversare occurring in the Mediterranean Sea and these can have synergistic impacts [6]. These driversinclude warming, invasive species, habitat loss, overfishing and pollution [4,7-10] and are already challenging marine organisms, ecosystems and the ecosystem goods and services that these seas are providing to human societies.

Ocean warming

The mean maximum summer seawater temperature of the Mediterranean Sea has risen by around 1 °C during the last three decades [11] and there has been an increase in the frequency and intensity of marine heat waves[12]. Seawater warming can kill organisms such as the mussel *Mytilusgalloprovincialis*[13,14] during summer and autumn periods when seawater temperature is above 26-27 °C. Shellfish farmers are being forced to sell their product earlier than they would otherwise wish to avoid harvesting loss mass mortalities during warm-water events[15].

Continued warming is likely to cause mass mortalities of the endemic seagrass*Posidoniaoceanica*([16]), invertebrates [12], including habitat-forming sponges and corals [17] as well as early life stages of a wide range of species [18]. In addition, increasing temperatures may also contribute to higher frequencies of disease outbreaks as warm-water microbial pathogens are expected to spread [19,20].

The increase in seawater temperature is altering biogeographic boundaries and leading to a meridionalization of the Mediterranean Sea [21] with northward shifts of species[7,22].Changes include an increase in abundance of eurythermal (*i.e.* wide thermal range tolerant) species and a decrease in cold stenothermal (*i.e.* narrow thermal range tolerant) species as well as northward species shifts and increase in mass mortalities during unusually hot summers [9]. For example, warm-water fish such asbarracuda(*Sphyraena* spp.),groupers (*Epinephelus* spp.), andround sardinella (*Sardinellaaurita*) have spread northwestwards. Certain cold water species have been replaced, for example the distribution of the cave-dwelling mysid(*Hemimysisspeluncola*) has contracted and been replaced by the warm-water mysid *H. margalefi* ([22]).

Invasive Species

Invasive warm water species of algae, invertebrates and fish are increasing their geographical ranges [23,24]. These tropical fauna and flora now form a significant portion of the biota in the Southern Mediterranean [25] where nearly half of the trawl catches along the Levantine coast consists of fish originating from the Red Sea [9,26]. Most of the 955 alien species recorded so far have been found in the Eastern Mediterranean [27] where many are detrimental to fisheries although some are now targeted commercially. In Cyprus, for example, the invasive puffer fish*Lagocephalussceleratus* (Tetraodontidae) is now out-competing native fish and their prey, such as the *Octopus vulgaris* (Octopodidae) and squid, which are becoming increasingly scarce [28].

Habitat loss/ degradation

Habitat destruction is one of the most pervasive threats to the diversity, structure and function of marine coastal ecosystems, leading to lower abundances and species richness and often allowing opportunistic species to prosper [29]. Habitat fragmentation can also impair the integrity, connectivity and functioning of large-scale processes leading to decreasing population stability and isolation of communities [30].

In the Mediterranean Sea, coastal habitats such as seagrass meadows, mollusc reefs (created by oysters, vermetids and mussels), coralligenousmaerl formations, and macroalgal assemblages on shallow reefs are examples of complex and highly biodiverse and productive ecosystems. They supply food resources, nurseries and shelter for species that are protected by international conventions, directives and action plans. Species invasion, unsustainable fisheries and aquaculture, sedimentation increase, water degradation, uncontrolled coastal tourism concentration, and urbanization can all have negative impacts on Mediterranean Sea habitats and associated species assemblages [8]. Continued loss of habitats to coastal development has triggered several international protective measures such as the development of Marine Protected Areas (MPAs), but their efficacy is questioned for improving resilience to climate change and acidification[31,32] as habitat loss continues apace.

Overfishing and aquaculture impacts

Overfishing in the Mediterranean Sea has had severe impacts both through direct overexploitation of targeted species such as small pelagics[33] and the Bluefin tuna [34]as well as through the damage of habitats and ecosystems. Trawling gear, dredges can degrade seabed habitats and harm non-target species such as cetaceans and turtles [35]. Bottom-trawling is a non-selective fishing method that causes a large mortality of discarded benthic invertebrates which can cause habitat destruction [35-37]. Massive prey depletion also leads to population declines of top predators such as marine mammals [38].

Given human population growth and the global decline in fisheries, aquaculture is predicted to increase to meet growing demand [39]. Some finfish farming can have a number of environmental effects on surrounding and downstream ecosystems [40]. Dissolved wastes increase the nutrient loading of the area and particulate wastes increase sediment deposition in coastal waters. The impacts of fishfarming on benthos in the Mediterranean vary considerably depending on site characteristics in particular on current and depth where the cages are located. Large-scale*Posidoniaoceanica* losses adjacent to fish farm cages have been reported across the Mediterranean [41].

4. Ocean acidification in the Mediterranean Sea

The Mediterranean Sea is low in nutrients except where coastsare affected by eutrophication, such as the Adriatic Sea. There is a general eastward pattern of increasing sea surface water temperature (SST), salinity (S), oxygen concentration, total carbon (C_T) and total alkalinity (A_T). Seasonal pH amplitudes can be very large (Fig. 6), particularly in the relatively shallow North Adriatic Sea,which also has a large seasonal temperature range. The SST, S, $A_T$patterns are mainly explained by evaporation coupled with highly alkaline freshwaters entering the basin from rivers and the Black Sea[42-44].The anthropogenic CO_2 concentration for the Mediterranean Sea[42,45,46] is higher than in the Atlantic Ocean and the Pacific Ocean [47,48]at the same latitude, and higher than other marginal seas in the northern hemisphere [49]. The high uptake of anthropogenic CO_2 in the Mediterranean Sea isrelated to its active overturning circulation [50]and relatively high $A_T$and temperature[51,52]. A dataset from the Northwestern Mediterranean Sea indicates a pH reduction of approximately 0.0018pH unit per year [2,3] from 1994 to 2006. For the next fifty years, an extrapolation of data from thistime series, (Dyfamed, central Ligurian Sea),leads to an estimated pH decrease of 0.07-0.13 units corresponding to a decreasing rate of 0.002 ± 0.001 pH units per year[53].

5. Ocean acidification impacts on fisheries and aquaculture

5.1 Direct effects on fish and shellfish

Shellfish

Bivalve mollusks are ecologically and commercially importantwithshellfish aquaculture is a particularly important activity for Mediterranean countries. However relatively few experimentsof the impact of ocean acidification have been undertaken in Mediterranean waters despite the hydrological and carbonate chemistry conditions having the potential to influence the sensitivity or resilience of bivalve species to ocean acidification. For instance, experiments conducted on the Atlantic side of the Gibraltar strait (Ria de Formosa, Portugal) in waters with high alkalinity levels showed that a pH reduction of 0.3 to 0.7 did not lead to significant reduction in growth of Mediterranean clams and mussels (*Ruditapesdecussatus*, Veneridae and *M. galloprovincialis*; [54,55]). Indeed, in these studies, higher alkalinity levels prevented any undersaturation with respect to aragonite and calcite in all treatments.

Large decreases in pH have, however, been showed to alter bivalve growth, even in Mediterranean waters. Michaelidis et al. [53], showed a significant reduction in shell and soft body growth of the Mediterranean mussel *Mytilusgalloprovincialis*(Mytilidae) following a long-term (~90 days) laboratory exposure to pH 7.3 [56], a level projected in the next 300 years.Similarly, in the Adriatic Sea, slight but significant reduced survival[57], growth and calcification of two marine bivalves (juveniles of the clam *Chamaleagallina* and of the mussel *Mytilusgalloprovincialis*)were induced by a relatively large decrease in pH (0.7) after 6 months of exposure [58].

Interestingly, Rodolfo-Metalpaet al.[59]showed that gross calcification rates by Mediterranean mussel (as measured by the incorporation of^{45}Ca) was not impacted by pH during most of the year, except in summer when calcification rates were significantly lower at pH 7.4, suggestingsynergetic negative effects of acidification and warming (for review [60]). Short-term factorial experiments performed in the Adriatic Sea revealed that acidification caused alterations in immunological parameters of adult bivalves, under sub-optimal conditions of temperature [57]. In the frame of the MedSeA project (http://medsea-project.eu; [61]), a year-long experiment onthe Mediterranean mussel *Mytilusgalloprovincialis*showed no lethal effects ofhypercarpnia (*i.e.*condition of elevated CO_2 in the seawater), while all mussels exposed to 3°C above ambient temperature died in August (temperature>27°C; [14]). Furthermore, ocean acidification had an effect on shell and soft-body growth in summer when temperature reached sub-optimal levels in the unperturbed temperature treatment, with significant loss of the periostracum, a protective organic layer covering the outer shell.

The impact of ocean acidification on molluscancalcifiers is not limited to growth and calcification as several physiological processes are affected by hypercapnia, as mollusks capacities to compensate for changes in acid–base status due to elevated CO_2 is believed to be somewhat limited.Michaelidiset al.[56] showed that long-term hypercapnia at pH 7.3 caused a permanent reduction in haemolymph pH in mussels from Greece and suggested that these organisms increase haemolymph bicarbonate levels derived mainly from enhanced shell dissolution in order to limit the degree of acidosis. In contrast, although intracellular pH decreased significantly with environmental hypercapniain the short-term, it was restored to normal levels in most tissues after several days of exposure.

The decrease in haemolymph pH was suspected to be the main reason of the decrease in oxygen consumption rates as observed at low pH, due to the inhibition of net proton transport across the cell membrane, a metabolic depression that is consistent with results from experiments performed on other marine invertebrates (e.g. [62]). Increased rates of ammonia excretion and associated decreases of O:N ratio suggested that the organisms exposed to low pH conditions increased their use of proteins as metabolic substrates. This could be responsible for damaging their cellular protein pool and therefore contribute to the observed drop in somatic growth.

Although very few data are currently available for bivalves in the Mediterranean Sea and none, to the best of our knowledge, on oysters that represent a significant part of Mediterranean shellfish production, it appears from laboratory experiments that lowered growth or altered physiology are not always observed under elevated seawater CO_2 conditions. Furthermore, evidence suggests that, at leastfor Mediterranean mussels [12, 57],warming and acidification will both extendthe temporal window when these organisms are exposed to sub-optimal conditions, most likely leading to decreased survival and growth in the coming decades.

Additionally, recruitment of organisms from the plankton is impaired in many groups as the larval stage is especially vulnerable to the effects of ocean acidification on their development - this appears to be especially true for molluskan species with implications for the shellfish industries [63]. In their recent review, Gazeauet al.[60] reported that embryonic and larval shellfish stages mainly respond negatively to ocean acidification regarding survival, development rate, growth and calcification. For oysters and mussels, studies showed that the negative effects of ocean acidification coincided with the beginning of shell formation (the trochophore stage), with no real impacts detected prior to this time and the decrease of larval development and growth is correlated to carbonate ions availability than to pH or aragonite saturation state[64-66]. Although mollusk embryo and larval responses to acidificationare not fully understood[67], the vulnerability of early-life stages is a potential bottleneck for population dynamics, and a concern for exploited mollusk [68].However, no studies have been performed on the effects of ocean acidification (and warming) on the larval development of bivalve species in the Mediterranean Sea.

Fish

Few studies have investigated the effect of hypercarpnia on Mediterranean fishes precluding a direct assessmentof the risk posed by ocean acidification on these marine resources.Nevertheless, based on the sparse current knowledgeacquired in other regions, mostly derived from laboratory-based experiments, the general understanding is thatadult fishes are not directly impaired by ocean acidification as their physiological performance allows them to cope with extracellular acidosis caused by ocean acidification (*e.g.*[69]). Furthermore, in contrast to shellfish, they are motile species and they can respond to acidification by shifting their geographic and depth ranges of distribution as already observed as a response to seawater warming. However, their efficienthypercania - compensation capacity does not prevent from downstream effects, for instance resulting in alterations of physiological and behavioral performances (see review [70]). As recently shown, CO_2 levels < 1000 µatm can interfere with crucial sensory behaviour in juvenile coral reef fish [71-73] or in sharks [74]. Surprisingly, one study showed a stimulation of breeding activity and reproduction success in the clownfish *Amphiprionmelanopus* (Pomacentridae) when exposed to CO_2 above 580 µatm[75]. These limited results do not allow an evaluation of the long-term consequences of the higherenergy cost for acid-base compensation and subsequent limit aerobic scope on fish fitness and individual performance [76].

A few direct effects of ocean acidification have been found on early-life stagesof fish, which are considered vulnerable because of the non-maturity of their physiological systems and acclimation capacities [76]. A decrease of survival and growth rate has been observed in an estuarine fish (*Menidiaberyllina*, Atherinopsidae) when exposed to high-CO_2(1000 µatm) just after egg fertilization, potentially affecting recruitment success at the population scale [77]. At CO_2levels above 5000 µatm, survival of Pacific tuna *Thunnusalbacares*larvae is affected[78]. Altered behaviour and otolith growth under highCO_2have been also highlighted, although responses appear as species-specific [79-81]. There are indications that increased CO_2 can negatively affect the metabolism and development of embryos of the Atlantic herring (a cold-water clupeid fish),*Clupeaharengus* (Clupeidae; [82]). On the other hand, recent data suggest that early life stages of cultured species such as the seabass, *Dicentrarchuslabrax* (Moronidae) are resilient to ocean acidification[83].

Regarding fished or farmed species inthe Mediterranean Sea, two studies suggest that adultsof the seabream*Sparusaurata* (Sparidae) are tolerant to seawater hypercarpnia and fully compensatefor extracellular acidosis even when exposed to CO_2 levels above 3000 µatm[84]. Furthermore, at lower levels (2000 µatm), a hypercalcification of otolith but no variation of somatic growth have been observed in juveniles of seabream suggesting their resilience to the ongoing ocean acidification [85].

In the Northwestern Mediterranean Sea, landings of warm-water clupeid anchovies (*Engraulisencrasicolus*, Engraulidae) and sardines (*Sardinapilchardus*, Clupeidae)are negatively correlated with high sea surface temperatureand low river runoff,that directly affect survival, growth, condition and reproduction of fish and impact recruitment success through lowered biological productivity in coastal areas suggesting that reproduction and recruitment success are affected by high temperature anomalies and land-based nutrient-related productivity of the coastal area [86]. In this context, this implies that warming may impact small pelagic populations in the Mediterranean Sea.No experimental studies have considered the cumulative effects of warming and acidification on fishes of commercial interest in the Mediterranean Sea.

5.2.Indirectimpacts of ocean acidification

In the previous section, the potential direct effects of ocean acidification and warming on commercial species in the Mediterranean have been considered. In the following section indirect effects of ocean acidification on fisheries and aquaculture will be considered.,These will be(i) changes to biodiversity, (ii) habitat loss and (iii) trophic web alteration.

Changes tobiodiversity

Thelarge biodiversity in the Mediterranean Seaprovides "use value" through sustainable use of marine organisms(e.g. algae and sponges supply a large variety of bioactive metabolites some of which are used to treat human diseases). This sea provides a wide range of food (high-quality protein, minerals and vitamin D and omega-3 fatty acids) with antioxidant properties and cardio and cancer protective effects and ornamental resources. Additionally, biodiversity generates a "non-use value" as bequest and existence value [87]. For instance, Langford et al.[88] report a non-market valuation study in the Aegean areaofthe public's willingness to pay (WTP) for conservation ofpatrimonial species such as the Mediterranean monk seal (*Monachusmonachus*, Phocidae), classified as the most endangered seal species in the world.– See Nunes and van den Bergh [89] or Remoundou et al. [90] for other studies on bequest and existence value of marine species. Large biodiversity enhancesintrinsic capacityfor adaptation of species (genetic diversity), resilience of ecosystem (specific richness within ecological guilds) and adaptation of dependent-population fostering shifts of fisheries targets.

Habitat loss

Many plants and invertebratesin the Mediterranean Seaform unique assemblages that provide essential habitats for fish and crustaceans and contribute significantly to the ecosystem functioning. Photosynthetic organisms, using CO_2 as a source for organic matter production, could potentially benefit from its higher availability. While Israel and Hophy[91] showed that a pH of 7.8 does not have any effect on growth and photosynthesis in a wide range of Mediterranean algae, Invers et al. [92] reported that this level of acidification enhanced photosynthesis in the important habitat forming Mediterranean seagrasses*Posidoniaoceanica* (Posidoniaceae) and *Cymodoceanodosa* (Cymodoceaceae). Field studies offVulcano and Ischia showed that seagrasses and certain seaweeds are able to benefit from elevated CO_2levels [93-95] and extend their cover area to the detriment of the diversity and abundance of calcareous algae. Calcifying coralline algae can also be important habitat formers and were found to be adversely affected by elevated CO_2 conditions, particularly when combined with high temperatures (seasonal temperature +3°C[96]). More recently, Kroeker et al. [97]showed that calcareous species might be physiologically able to persist in pH condition predicted for the near-future ocean but suffer from the development of a higher competitive ability of fleshy, non-calcareous seaweeds. Overall, current studies indicate that ocean acidification will cause major shifts in the microalgae and seaweed communities. The potential loss of some of these organisms is a great concern as they form important habitats for fish, shellfish and a wide range of other organisms.

Results obtained in the framework of the MedSeA project also suggest dramatic changes across ecosystems and taxa under ocean acidification and warming conditions. Thus, sea grass meadows are expected to suffer from elevated seawater temperature and invasion by non-indigenous algae species, which benefit from increased CO_2 and elevated temperature. Whilst calcified organisms generally fare badly as CO_2 levels increase, some can proliferate in an uncalcified form (e.g.*Padina spp.*, Dictyotaceae; [94]).

Moreover, the slow growth or even extinction of key calcifiers may detrimentally affect major bio-construction on vermetid reefs and coralligene reefs where these supply the cementing calcium carbonate that keeps these reefs intact [98]. Vermetid reefs along the Levant coast are already facing extinction, which is likely to lead tomajor loss of biodiversity and shore erosion. Calcifying corals that form important habitats for fish, supporting their own fisheries, attracting recreational tourism [99] and supporting local economies appear to be particularly vulnerable [59]. For example, it has been recently demonstrated that there are detrimental effects of ocean acidification on the economically important Mediterranean red coral endemic species*Coralliumrubrum,*Coralliidae, mainly due to the elevated solubility of its Mg-calcite skeleton[100]. In turn, the growth and calcification of cold-water corals maynot being affected by CO_2 levels projected for the end of century after long-term exposure [101,102]. Nevertheless, considering that information on this acclimation of calcification in natural environment are scarce and that corals live close to their upper thermal limits in Mediterranean Sea, the fate of these deep-sea builders of hotspot biodiversity remain uncertain.

As both calcifying and non-calcifying habitat-formingspecies are likely to suffer under warming and acidification this will lead to malfunction of the respective habitats and have knock-on ecological effects, limiting the biodiversity and functional diversity of ecosystem, *i.e.* limiting resources for targeted species and nursery grounds and potentially altering the sustenance of fish stocks.

Oligotrophic coastal habitats such as those in the Mediterranean Sea are dominated by slow growing species and intricate food webs. Habitat losses can be considered irreversible, as it would take centuries following the cessation of disturbances for ecosystems to return to their original state.

Trophic web changes

The abundance of marine resources, including both mollusks and fishes, are strongly dependent on the structure and functioning of the regional trophic webs, and could be indirectly impacted if the increasing CO_2 levels affected abundance and quality of the lowest trophic levels (i.e. phyto- and zooplankton). Benthic food webs in the Mediterranean are supported by the productivity ofmeadows of the seagrass*Posidoniaoceanica*. This benthic productivity could decrease by the end of the century due to the negative impacts of raised seawater temperature directly on the seagrass and through a significant loss of epiphytic communities by higherpCO_2 conditions foreseen[103]. Recent studieshighlighted a possible shift in pelagic productivity from large phytoplankton towards the smallest pico- and nano-plankton as a result of future ocean acidification – see Riebesellet al.[104]and warming [105].

The cell density and biodiversity of coccolithophoreswere also found to decrease along a natural pH gradient off Vulcano Island [106].In addition, an impact on the calcareous phytoplankton dominant species has been already observed in a time series in the Gulf of Lyon mainly linked to ocean acidification [2]. Nevertheless, mesocosm experiments carried out in oligotrophic area in Mediterranean demonstrated that ocean acidification did not affect the primary, POC, DOC production and community respiration [107], as the plankton communities are first limited by the nutrient availability. Such a substantial change in the base of the pelagic food web will have direct consequences for the structure and functioning of the higher levels of food web. At the next trophic level, zooplankton is a major dietary component for fish, including small pelagic such as sardines. The larval stage of pteropods*Cavoliniainflexia* (Cavoliniidae) appeared directly impacted at pH projected for the end of century, and displayed malformations and lower shell growth [108]. While it had been thought that that copepods would be not affected by ocean acidification, recent work questions the ability of the Mediterranean *Acartiaclausi (Acartiidae)* to cope with combined stress of acidification and warming[109].

Field studies at the community scale highlighted that decreasing pH tends to lead to a decrease in the species richness and biomass causing a simplification of the trophic web functioning [110]. In Greece, ocean acidification around natural CO_2 vents stimulates macro-algal communities but this increase in biomass is controlled by herbivorous species, with shifts in abundance and composition from sea urchin to herbivorous fish (Baggini et al., 2015).This observation suggests that a bottom-up effect of ocean acidification on seaweed biomass could be controlled by a top-down process consisting of a shift within the same trophic level from species vulnerable to CO_2 to more tolerant species.This shift of community to a few generalist species could lead to another cause for concern, that is a proliferation of non-calcifying cnidarians (jellyfish and anemones) resilient to or benefiting from warming and/or acidification [111,112]. Finally, recent studied performed in sedimentary habitats in the natural CO_2 gradients off Vulcano, Italy, have revealed increased ocean CO_2 is associated with changes in sediment bacterial community composition but that most of these organisms are resilient [113]. The consequences of these microbial diversity shifts on the benthic trophic web and biogeochemical cycles remain still unclear. As the Mediterranean Sea is threatened by risingCO_2, it becomes increasingly essential to assess the socio-economic value of these important systems, including ocean acidification impacts on ecosystem functioning and trophic web changes.

Human health impacts

Beyond the impact of ocean acidification on the production of marine resources, the quality of seafood might be compromised by future ocean conditions and may increase the safety risk for human consumers. Concomitantly with increased eutrophication and stratification of the Mediterranean Basin, ocean acidification is expected to foster Harmful Algal Bloom (HAB) in coastal waters[114,115]. Proliferation of these harmful microalgae can cause damage to the environment directly by affecting exposed organisms as well as threaten human health through contaminated seafood consumption [116]. Temperature appears as the main factor driving harmful algae abundance, as observed for ciguatoxin*Gambierdiscusspp*, Goniodomataceae[117] or saxitoxin*Alexandriumcatenella*, Goniodomataceae[118]. In the Mediterranean Sea, the palytoxin-producing dinobiont*Ostreopsis ovate*, Ostreopsidaceae is extending its distribution, with definite consequences on human health (irritation, cough, fever and respiratory problems; [119]). Moreover, *Gambierdiscustoxicus*, the main causative agent of ciguatera poisoning, normally has a tropical or subtropical distribution but has recently been reported in waters around Crete. While there are few studies investigate the potential impact of ocean acidification on the HABs, it has been recently demonstrated that CO_2 combined with limited nutrient enhanced karlotoxin and domoic acid production by*Karlodiniumveneficum*, Kareniaceae[120] and*Pseudonitzschiafraudulenta*, Bacillariaceae[121], respectively.

Ocean acidification and warming will occur in a background of chronic contamination of the coastal area through human discharges of contaminants. The changes of seawater chemistry caused by increased CO_2 can modify the bioavailability of contaminants such as trace elements [122]. As a consequence of acidification, the bioaccumulation of metals in organisms such as cephalopod or bivalves is expected to rise under a constant contamination pressure[123-127]. Beyond the direct toxicological risk for marine animals, seafood safety with regard to human consumers might be compromised by increases of both total metal concentrations and of the bioaccessible fraction of contaminants (Belivermis et al., unpublished data). Indeed, oysters can accumulate high levels oftrace elements, such as Zn, in their soft tissues in the form of metabolically inert metal-rich granules [128]. These Mg/Ca carbonate granules are known for their potential for buffering the extracellular pH [129] and thus might be easily dissolved when oysters are experiencing hypercapnia. In this context, the ocean acidification mayimpact strategies for metal detoxification and thus the Trophically Available Fraction (TAM) that drives theirbioaccessibility and transfer of these metals to higher trophic level.

6. Reflections and conclusive remarks

Future ocean acidificationand increased water temperatures, if global CO_2 emissions to the atmosphere continue unabated, area threat to the Mediterranean Sea and will negatively impact its biodiversity and productivity and in turn impact key social and economic services it provides human communities in the region (e.g. shellfish aquaculture, fisheries and tourism).

Key messages emerge from our analysis:

1.A greater understanding of how marine systems are affected by ocean acidification and warming is required through setting up long-term, basin scale monitoring of carbonate system dynamics and regular socio-surveying of Mediterranean warming and acidification impacts on selected production sectors.

2. More information on the responses of local marine species of high economic interest, including both fish and shellfish,and the ecosystems and food webs they depend on to both ocean acidification and warming is required.

3.Projections of future acidification and warming in regions supporting important fisheries,aquaculture and tourist industries is required to helptheir timely adaptation to a changing sea. .

4. Enhance adaptive capacity within the fisheries and aquaculture sectors, especially in the southern Mediterranean basin where dependence on seafood for animal protein source and income is strong requires development through:

a)technical support and advice to the aquaculture sector in monitoring the risks associated with acidification and warming and understanding future projections, risk maps, risk analysis methods and how they may change with time and levels of acidification and warming

b) development of best practices for adaptive management

c) selection of resistant species or strains to increasing acidification and warming.

d) development of a communication strategy through public-private-partnerships of stakeholders so that there is an exchange of knowledge with parties or sectors most vulnerable to a changing Mediterranean Sea.

5. An involvement of all stakeholders in the societal and industry response to a changing Mediterranean Sea including marine and coastal managers, conservation practitioners, industry representatives, science policy advisors and policy makers, and other stakeholders and end-users, mainly from countries bordering the Mediterranean Sea. This approach can often determine the success or failure of a policy action [130].

6. An integrated economic valuation of other key economic sectors other than fisheries, such as tourism, is neededto help put an economic value to the losses that may be incurred by increasing acidification and warming of the Mediterranean Sea so that policy makerswill have the costs/benefits of policy action as well as the costs of policy inaction with regard to mitigation of and/or adaptation to acidification and warming. .

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Zn) bioaccumulation in the eggs of the common cuttlefish, *Sepia officinalis*, Biogeosciences 6 (2009) 2561-2573.
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Figures Captions

Figure 1. Mediterranean Sea and bordering countries.

Figure 2. Trends of capture fisheries and aquaculture production in countries of the General Fisheries Commission for the Mediterranean (GFCM) from 1991 to 2010. Data source: (*) FAO Capture Production in GFCM statistical area (release data: February 2012) – (**) Production in GFCM countries (aquaculture from Atlantic areas excluded) – SIPAM-FAO Aquaculture Production 1959-2010 (Released date: March 2012).

Figure 3. Capture production of the Mediterranean Sea fisheries in 2011. Data extracted from "GFCM Capture Production" databases from FAO.

Figure 4. Trends of landings (in tonnes) of sardine (*Sardinapilchardus*), anchovy (*Engraulisencrasicolus*), sardinella (*Sardinellaaurita)* and other small pelagic fish in Mediterranean Sea from 1970 to 2011. Data extracted from "GFCM Capture Production" databases from FAO.

Figure 5: Bivalve production from aquaculture in Mediterranean Sea. Data extracted from "Global aquaculture production" databases from FAO.

Figure 6. Spatial distribution of seasonal pH ranges driven by physical processes only (from the high-resolution CMCC model).

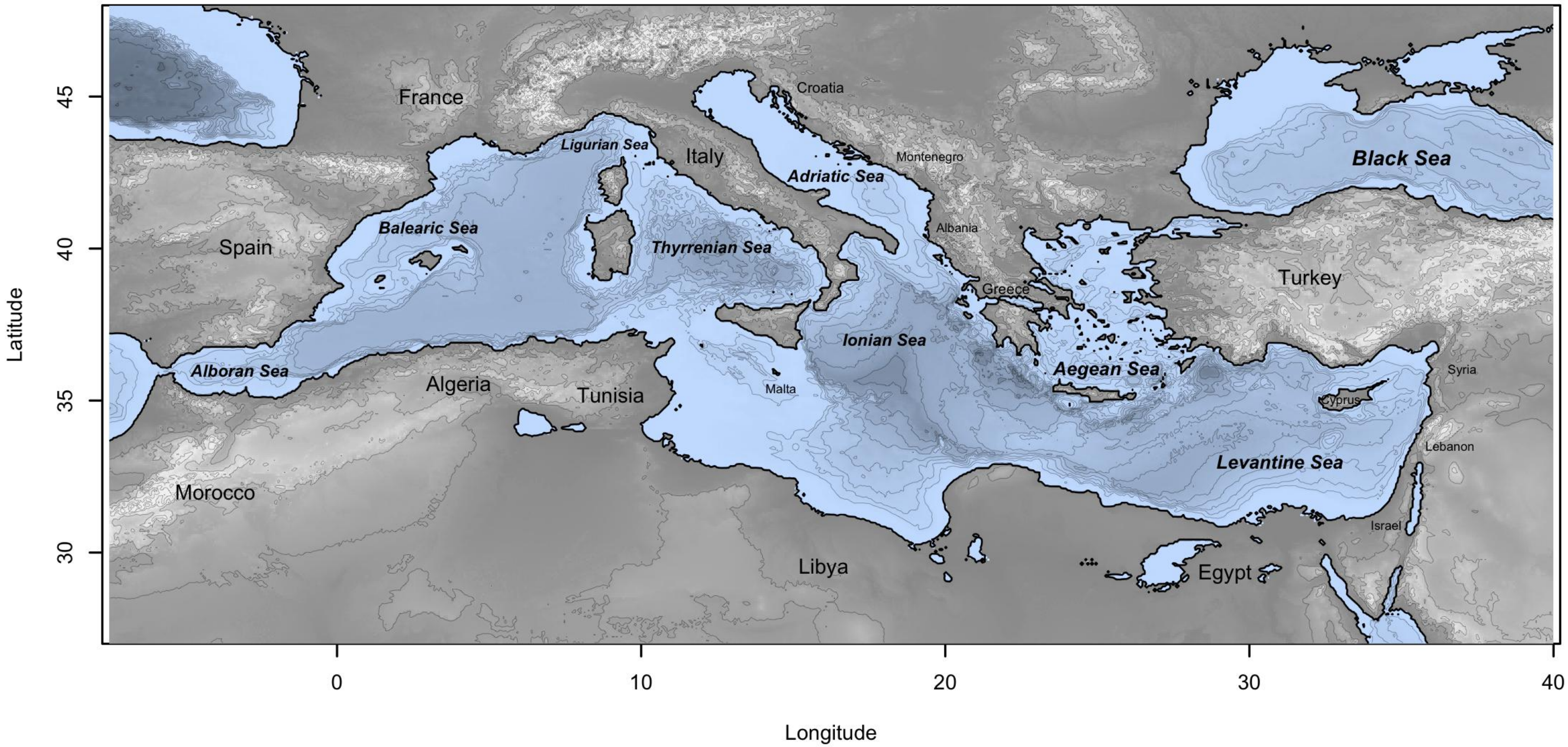
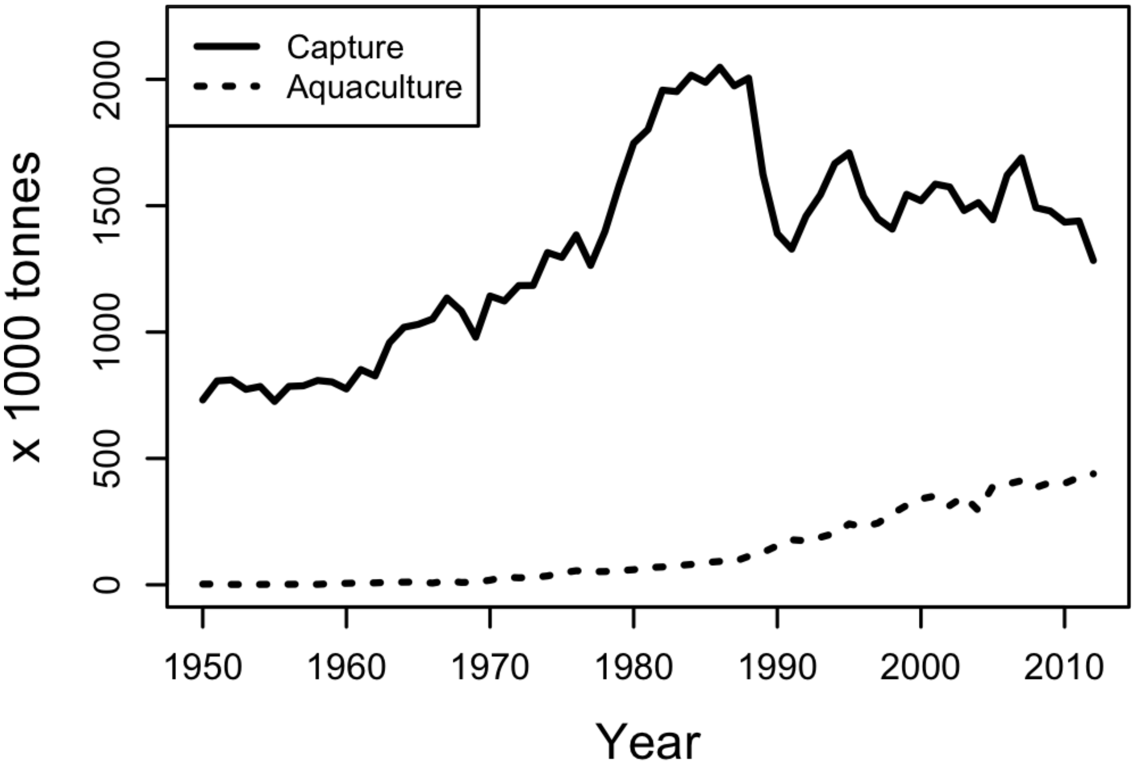

France
Croatia
Italy
Ligurian Sea
Montenegro
Adriatic Sea
Black Sea
Balearic Sea
Spain
Thyrrenian Sea
Albania
Greece
Turkey
Ionian Sea
Alboran Sea
Aegean Sea
Syria
Algeria
Tunisia
Malta
Cyprus
Lebanon
Levantine Sea
Morocco
Israel
Libya
Egypt
45
40
35
30
Latitude
0
10
20
30
40
Longitude

Figure 1


Capture
Aquaculture
x 1000 tonnes
0
500
1000
1500
2000
1950
1960
1970
1980
1990
2000
2010
Year

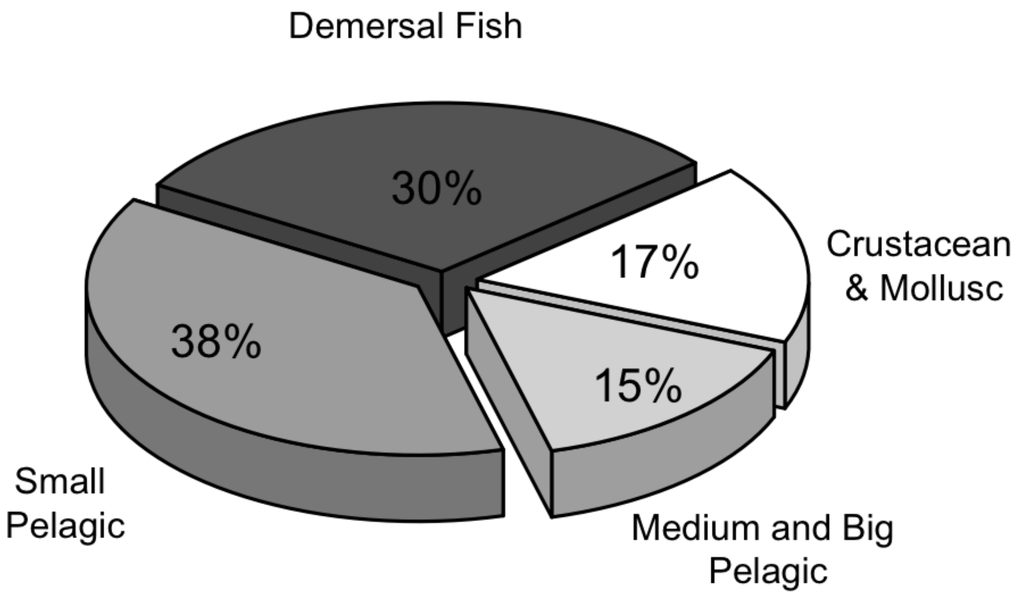

Demersal Fish
30%
17%
Crustacean & Mollusc
38%
15%
Small Pelagic
Medium and Big Pelagic

Figure 3

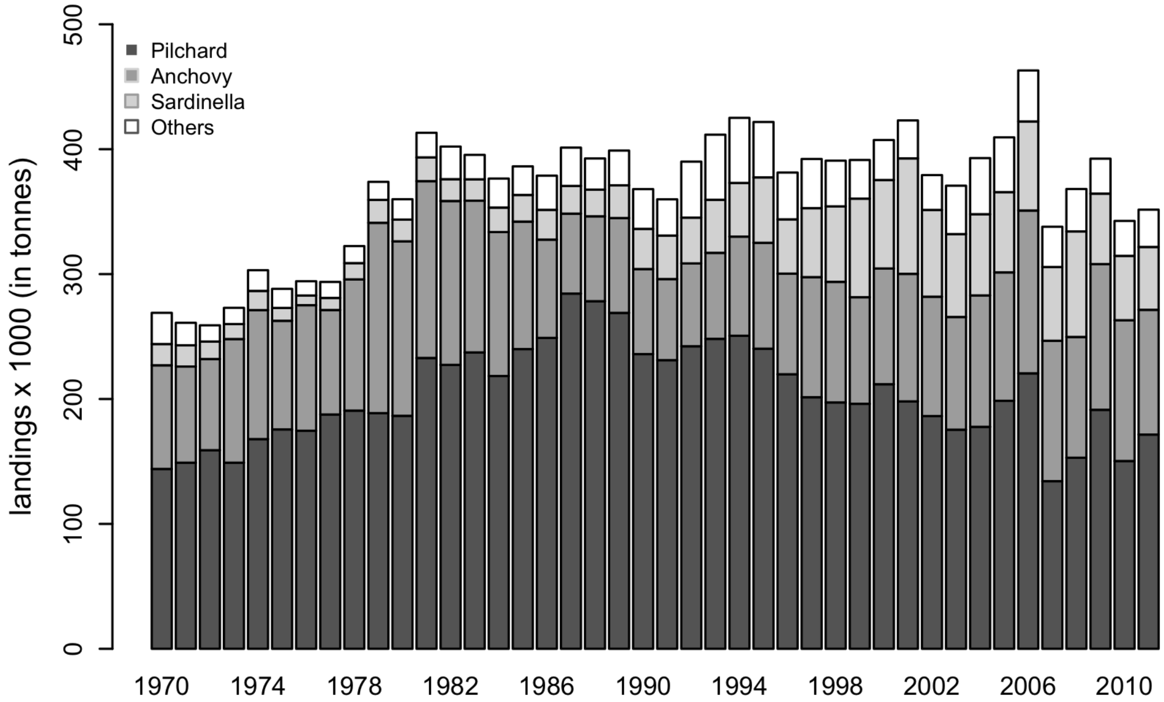

Pilchard
Anchovy
Sardinella
Others
landings x 1000 (in tonnes)
0
100
200
300
400
500
1970
1974
1978
1982
1986
1990
1994
1998
2002
2006
2010

Figure 4

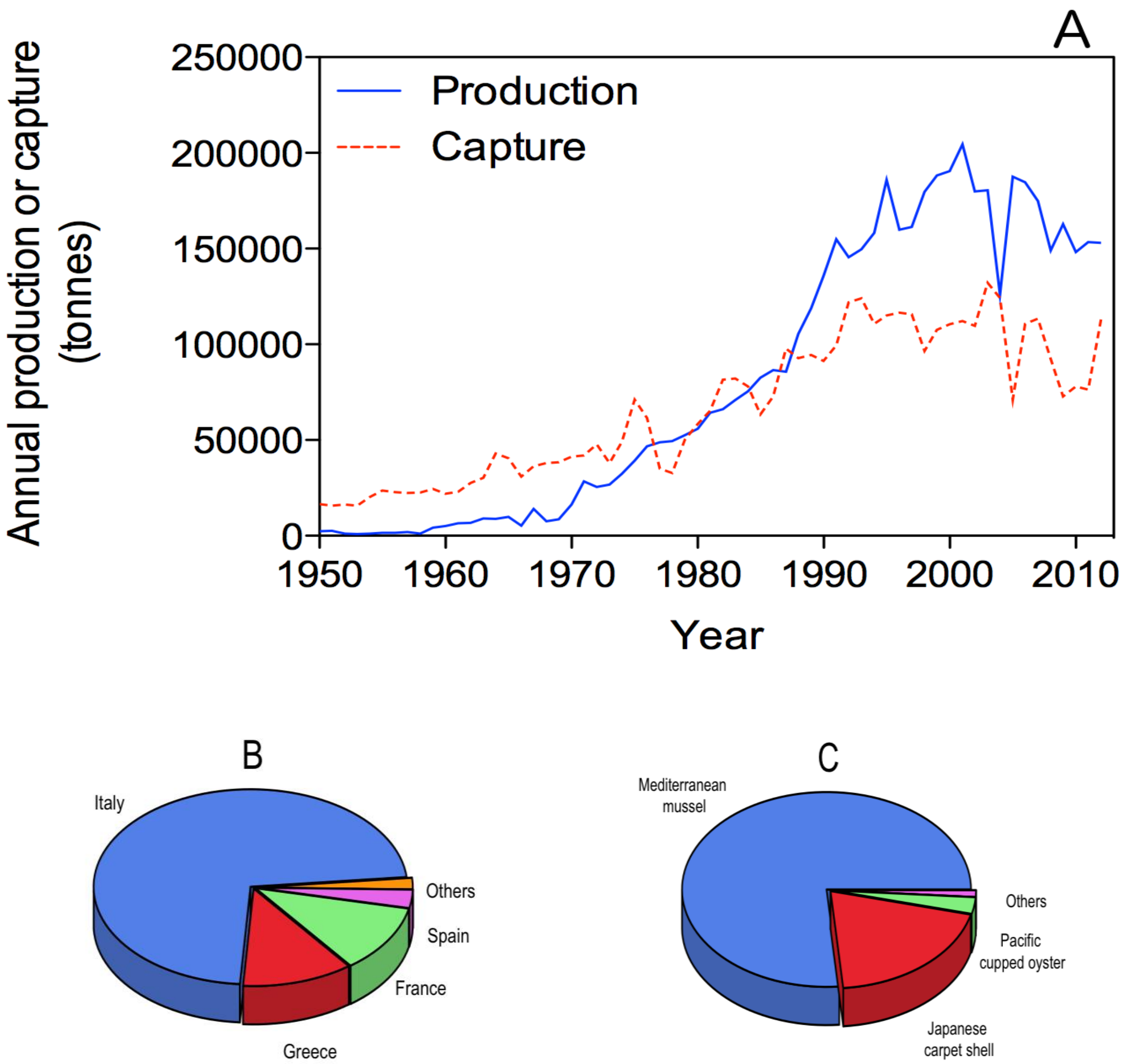

A
Annual production or capture (tonnes)
250000
200000
150000
100000
50000
0
Production
Capture
1950
1960
1970
1980
1990
2000
2010
Year
B
Italy
Others
Spain
France
Greece
C
Mediterranean mussel
Others
Pacific cupped oyster
Japanese carpet shell

Figure 5

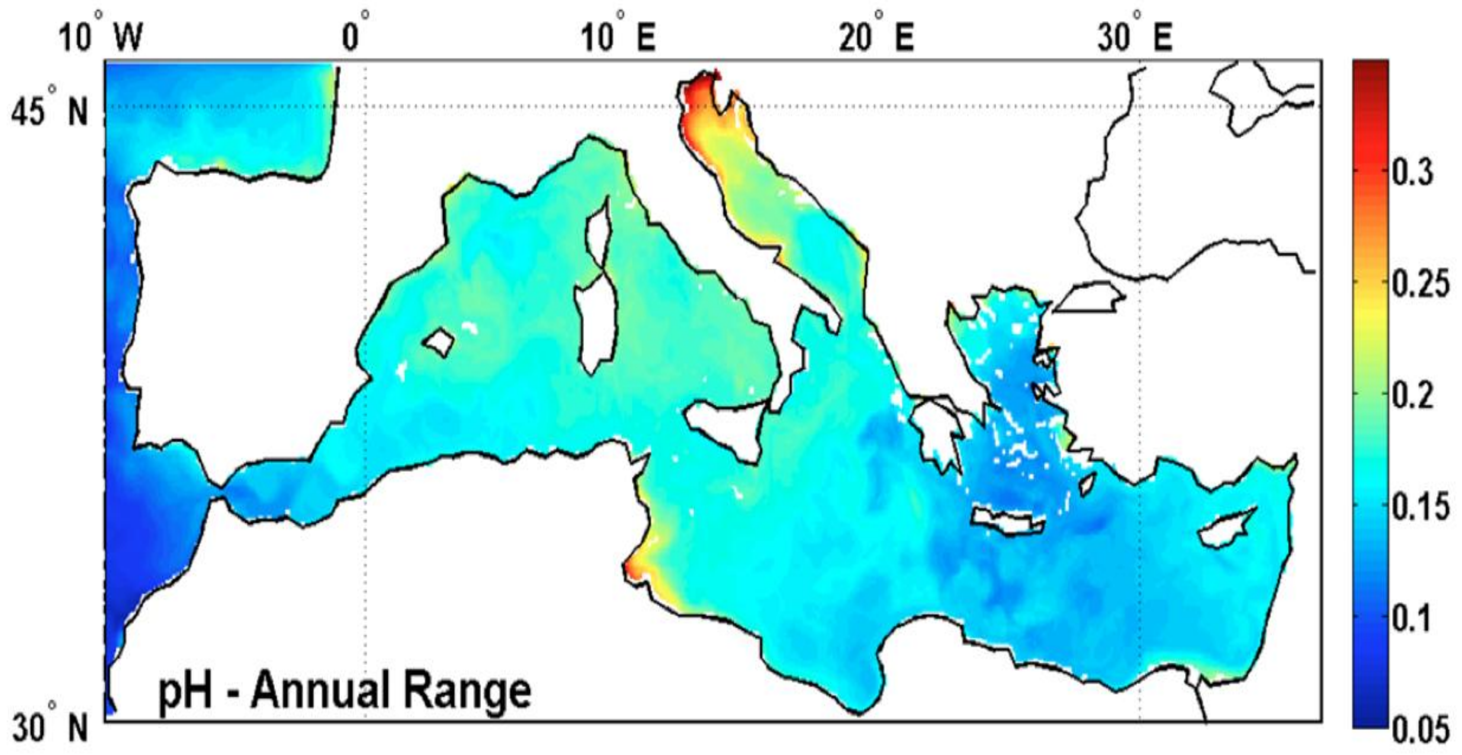


Figure 6